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HF MODEM TEST AND EVALUATION

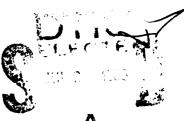
Signatron, inc.

Lynn K. Cosell, Stephen R. Kolek, Peter Monsen and Linda C. Perry

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> The objective of this program was to evaluate a recently developed, bandwidth efficient, Decision-Feedback Equalizer "Fast DFE" serial modem for radio communications in the High Frequency (3-30 MHz) radio band. The experimental model of the modem is realized on an AP-120B array processor. Tests of nonfading, flat and frequency selective fading were performed using a separate AP-120B array processor as the channel simulator. Successful performance of the modem operating at 2900 bps in a 2.7 KHz band-

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width was demonstrated on channels with 20 fade rates up to 1 Hz and multipath delay values up to 5 milliseconds. Under slow fading conditions a significant implicit gain due to the multipath is realized. In a comparison with parallel tone modems, the Fast DFE modem significantly outperformed the USC-10, ACQ-6, and MX-190 modems in all test cases.

Results reported here show considerable promise of the Fast DFE configuration and there is every indication that the preliminary design implementation which was tested can be further optimized for superior performance.

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1.0 INTRODUCTION

An HF serial data transmission modem has been developed at SIGNATRON. The modem runs in microcode on a Floating Point Systems AP-120B. The tests reported here were performed on the Microcode modem model operating at an information rate of 2900 bps. The Decision-Feedback Equalizer (DFE) was successfully developed at SIGNATRON in a previous troposcatter application for the signal processing functions of intersymbol interference removal and implicit diversity gain. Based on the DFE, a new fast tracking algorithm has been developed especially for the HF channel application. This algorithm is significantly less complicated than matrix update Kalman algorithms which have been suggested for HF use.

1.1 Background

Communication via the HF radio channel is limited primarily by fading multipath effects and atmospheric noise condi-For shorter ranges of communication using the relatively constant surface wave component or under sporadic E reflection conditions, the HF channel can be characterized as a non-fading radio channel with excellent performance characteristics. tunately, the more typical applications involve multiple fading skywave paths. Historically, this multipath phenomenon has limited achievable data rates because of multipath induced intersymbol interference (ISI). The effects of ISI can be reduced by transmitting data in a parallel data subchannel format with receiver blanking techniques to eliminate the pulse to pulse inter-The parallel data subchannel format has the disadvanference. tage of a large peak-to-average ratio which reduces the biterror-rate (BER) efficiency with a peak power limited HF trans-Moreover, there exists an implicit diversity capability associated with the multipath structure of the channel which is not fully realized with this parallel channel format. Since a modest amount of diversity can provide a large dB improvement in performance, previous attempts to capitalize on the channel implicit diversity have been undertaken. The CODEM [1.1] system used a parallel subchannel format with coding across the frequency band to realize some of the diversity effect. However, the diversity improvement was small and the technique suffered from a large peak-to-average loss and was sensitive to adjacent subchannel interference.

The implicit diversity can be more efficiently realized with a serial data transmission mode where the symbol length is on the order of the multipath spread of the channel. The resulting intersymbol interference must, of course, be compensated for by a signal processor technique. One signal processor approach applied on the HF channel utilized a Fano decoding algorithm to decode the natural convolutional code structure of the channel. However, channel tracking difficulties and the catastrophic failure characteristic of the Fano decoder combined to produce significant dropout conditions and restart difficulties.

In a troposcatter application, a Decision-Feedback Equalizer (DFE) [1.2] was developed to exploit the implicit diversity inherent in multipath and combat the deleterious effects of intersymbol interference. Eight engineering models of the DFE modem were produced under the Army sponsored Megabit Digital Troposcatter Subsystem (MDTS) [1.3] program by the GTE Sylvania/SIGNATRON team. This modem has been successfully tested, first on channel simulators [1.4], then and in field tests in New York and in Europe. Because of the DFE modem ability to provide implicit diversity while combatting intersymbol interference, the data rate capability of strategic troposcatter links was increased by approximately an order of magnitude. The success of the MDTS DFE modem has generated much interest in converting strategic analog troposcatter links to digital transmission.

At the same time, successful application of equalizer technology to digital transmission over troposcatter has spurred interest in a similar effort for HF radio channels. For the HF channel, however, it is more difficult to track the channel variations because the ratio of data rate to channel fade rate is smaller and, in addition, the ratio of multipath spread to symbol length is larger. On the positive side, many HF channels do not now employ diversity techniques so that the implicit diversity improvement afforded by equalizer technology may be much larger than that realized in the troposcatter application.

Other factors that have contributed to an increased interest in the potential use of serial transmission techniques in HF applications are the complexity of parallel tone modems, their susceptibility to frequency selective fading, and their poor bandwidth utilization. Two major problems have inhibited the development of serial data modems on equalizer technology: fast tracking requirements and large multipath spread-to-symbol inter-The former is the more serious problem presented by the HF application. The added intersymbol interference due to increased multipath can be accommodated by an expansion of the transversal filter length in the equalizer. This expansion is approximately linear with the amount of multipath. tracking problem, SIGNATRON's past experience in DFE applications to troposcatter and to shipboard HF transmissions has shown that the conventional Least-Mean-Square (LMS) or gradient algorithm will not provide the tracking capability required in the HF channel application. On the other hand, results on the use of a Kalman/Godard algorithm for telephone channels suggest that this algorithm may be the fastest one available and thus may be capable of significant improvement over the LMS algorithm in the HF application. This improvement would have to be gained, however, at the cost of a significant increase in adaptation algorithm complexity.

In contrast to the LMS algorithm, the Kalman algorithm requires matrix computations every update rather than vector com-The order of the matrix, or vector in this computation is equal to the total number of transversal filter taps in the equalizer. Recognizing the potential as well as the difficulties of the Kalman approach, SIGNATRON in an internally funded effort, has examined alternate adaptation approaches in an effort to find an equalizer design with the Kalman efficiency but without the requirement for matrix updates. To this end, SIGNATRON using its computer facility performed extensive simulations resulting in the development of the most attractive alternative to the Kalman algorithm. This alternative, which has been named the "Fast DFE", and which uses vector updates rather than matrix updates, has been shown to have performance nearly as good as the Kalman approach. The Fast DFE concept is the basis for the design of the HF modem which is tested in this program.

1.2 Program Summary

A test effort to evaluate a new serial modem approach for HF applications has been completed. The HF modem operates at 2900 bps information rate and uses a decision-feedback equalizer for processing the HF multipath. The test program included extensive tests under nonfading and fading channel conditions. Both the modem and channel simulator [1.5] were realized in independent programmable array processors for these tests. Test results show that the SIGNATRON HF Modem significantly outperforms conventional parallel tone modem approaches. The SIGNATRON modem has comparable performance with a Harris Corporation serial tone modem [1.6] and operates successfully at higher fade rates where operation of the GTE Sylvania [1.7] modem is not possible.

Testing of the Signatron HF modem was not performed with a hardware model over real HF links. Testing was limited to computer software simulation of both the modem and the HF channel.

1.3 Outline of Final Report

System considerations in the development of the SIGNATRON HF modem are presented in Section 2. This section also contains a block diagram and description of the Fast DFE modem. A description of the test configuration is given in Section 3. Section 4 presents the test results. A comparison with other serial modem tests is contained in Section 5. In Section 6 mendations for future work.

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2.0 SYSTEM CONSIDERATIONS

A company sponsored independent research and development program at SIGNATRON has led to the development of a new serial data HF modem. The SIGNATRON modem utilizes a modified version of the Decision-Feedback Equalizer (DFE) which has been successfully applied by the Company in troposcatter communications. This section begins by discussing the selection of serial data modulation over parallel tone modulation. The new SIGNATRON HF modem is then described.

2.1 Serial vs. Parallel Tone Modems

The HF channel contains fading multipath returns which may spread over a delay interval on the order of 5 milliseconds. A 2400 bps data rate using a Quadrature Phase Shift Keying (QPSK) modulation technique uses a 1200 Hz modulation symbol rate. With this symbol rate the modulation symbols repeat every 0.833 milli-With reference symbols added, each modulation symbol seconds. would become even shorter. Multipath delay of up to 5 milliseconds would dramatically smear symbols less than a millisecond Consequently, any serial modem technique must deal with significant InterSymbol Interference (ISI). In present day HF modems the solution to the ISI problem has been to employ parallel subchannels each with a low rate modulated signal. the subchannels are then at a low rate, the modulation symbol can be made longer than the multipath spread and the effect of ISI smearing is reduced. The parallel tone technique which is typified by the original Kineplex system has the following major disadvantages:

- Parallel modulation tones leads to a high peak-to-average ratio (~ 7 to 9dB) which in a peak power limited HF radio application significantly increases transmit power requirements for a fixed detected signal quality.
- The parallel tone format does not generally exploit the inherent div sity protection provided by the fading multipath channel structure. By contrast, the serial format can take advantage of the implicit diversity available through the multipath structure and can thus provide very large performance gains. This is a critical advantage because many HF systems have no explicit space or frequency diversity.

Because the single tone, serial data modulation approach inherently offers better performance potential for HF applications, SIGNATRON has focussed its research on this technology. We have demonstrated that a new adaptive equalizer can successfully track the channel multipath structure, can mitigate the ISI and can realize the potential implicit diversity gain inherent in the multipath. The peak to average ratio for a 2400 bps serial rate modem for a spectrum confined to the standard voice band is on the order of 1 or 2 dB. The improvement of 5 to 8 dB in peak-to-average ratio together with the implicit diversity gain lead to a very significant transmission quality differential of serial over parallel tone modem techniques.

2.2 Equalizer Adaptation

An equalizer uses an error signal generated internally to adapt tap weights in a tapped delay line filter. The error signal contains ISI and noise contributions which are to be minimized. The effectiveness of this error signal in decision directed adaptation is dependent on the ratio of the data rate and the rate at which the channel changes. The slower the symbol rate the smaller the number of independent samples during the in-

terval during which the channel changes and the harder it is to track the change. On the other hand, the higher the symbol rate the more ISI. By way of an interesting comparison, in troposcatter the information rate is on the order of a megabit/second while even the fastest channel fluctuation rate due to airplane reflections is only 100 Hz. Thus the ratio of data rate to the rate of change in the channel ranges from 10⁴ to 10⁶. In HF transmission the ratio of the modulation symbol rate to the fastest channel rate fluctuations is smaller as information rates of a few kilobit/second must allow for tracking channel rates on the order of 1Hz, thus the same ratio is 10³. The classic Least-Mean-Square (LMS) algorithm widely used in telephone and microwave radio equalizer applications fails to track under these conditions.

The tracking failure of the LMS gradiant algorithm is due to the slow convergence caused by the smaller eigenvalues of the correlation matrix of the tap signals in the equalizer. Tracking convergence can be speeded up by modifying this correlation matrix by a transformation that generates equal eigenvalues. One tracking solution which achieves this result is the Kalman filter. In a study program for NOSC [2.1], SIGNATRON developed a software simulation of these algorithms. Work at SIGNATRON and at NOSC led to a comparison of an LMS and Kalman filter equalizer for an HF application. The performance of these respective systems under frequency selective fading conditions is illustrated in Figure 2-1. The irreducible error rate of the LMS system is due to slow tracking modes which can not keep up with the channel fluctuations.

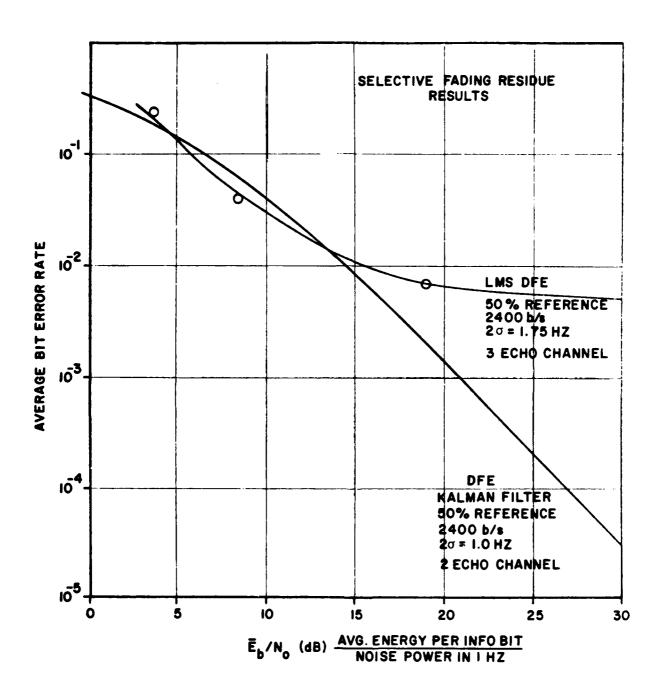


Figure 2-1 LMS and Kalman Filter Equalizer Performance

Unfortunately, the greatly improved performance of the Kalman filter over the LMS adaptation comes at the considerable cost of a greater complexity. In general the LMS equalizer uses vector updates of the equalizer tap gains while the Kalman filter requires matrix updates. Thus the complexity of the Kalman solutions is on the order of the square of the LMS approach.

SIGNATRON has invented and developed a new adaptation approach called the Fast DFE which uses the principle of equalizing the multiple eigenvalues in the DFE to speed up the rate of convergence (i.e., channel tracking speed) but employs vector updates rather than matrix updates, thus reducing the complexity of the tap-adaptation algorithm. The Fast DFE approaches closely the performance of the Kalman filter but avoids the Kalman filter complexity.

2.3 Atmospheric Noise Due to Lightning

Lightning discharges cause a burst noise on the order of a few milliseconds. This phenomena has less effect on parallel tone modem techniques because the noise burst is short compared to the modulation symbol length. For a serial rate modem however the resulting noise burst will wipe out more than one modulation For 2400 bps digitized speech such as from Linear Predictive Coders (LPC), which can tolerate higher error rates, the effects of isolated burst errors may be negligible. For digital data transmission, however, low error rate is required. those conditions, atmospheric noise bursts due to lightning must be mitigated through an error correction and interleaving tech-In the SIGNATRON modem design an interleaver disperses nique. the burst errors due to lightning over a longer block of data, so that erroneously detected symbols can be corrected by a random error correction coding technique. In nonvoice application, the interleaver delay may be selected long enough to provide a time diversity advantage.

2.4 Fast DFE Modem

The SIGNATRON modem uses a modified Decision-Feedback Equalizer (DFE) to eliminate ISI and provide implicit diversity from channel multipath. The basic DFE consists of a forward filter equalizer (FFE) which processes the input signal and a backward filter equalizer (BFE) which processes the detected QPSK The principle of the DFE for a fading channel application is covered by a U.S. patent [2.2]. In the HF modem design the original adaptive DFE, developed for the troposcatter application and employed in the MD-918 modem [2.3], has been speeded up for HF use through a partitioning of the FFE into two sections. The first section is an adaptive matched filter or diversity combiner which copes with changes in the channel structure. The second section is the forward filter itself which copes with the ISI. An adaptive orthogonal filter preprocessor has been added between the matched filter and the forward filter in order to equalize the eigenvalues of the tap correlation matrix and speed up the adaptation rate. A significant advantage of seqmenting the FFE into separate functional blocks is that the time constants in each block can be optimized to suit its function. This new adaptive DFE called the Fast DFE, was also invented by Dr. Monsen, and was recently issued a U.S. Patent [2.4]. the fast DFE uses vector updates rather than matrix updates (as in the Kalman algorithm), the complexity of the Fast DFE is comparable to that of a conventional LMS equalizer, even though the convergence rate is better.

Some of the early equalizer designs for the HF channel used a training sequence followed by a block of data (e.g., Di Toro, [2.5]). This approach was never fully successful. The SIGNATRON modem interleaves a proportion of reference symbols into the data stream. Adaptation is achieved by combining the reference-directed adaptation, which uses the reference symbols, with decision-directed adaptation, which uses decisions from the

detector. The advantage of this approach is that both reference-bearing symbols and data-bearing symbols are used to track the channel; thus, the proportion of symbols devoted to the transmission of reference can be reduced. With a lower proportion of reference symbols, either the data rate can be higher or the symbol interval can be lengthened to reduce ISI. Furthermore, with an interleaved reference, channel tracking is always up-to-date.

The SIGNATRON Fast DFE was originally developed and reduced to practice in a non-real time Fortran simulation. Performance results from this Fortran simulation (see Figure 2-2) were promising and the company undertook an internal research and development program to develop the Fast DFE algorithm on a programmable processor. For a simulation of the Fast DFE, the AP-120B programmable array processor was chosen. The modem resident in the AP-120B was tested by transmitting over an HF channel simulator which was resident in another AP-120B array processor. Our PDP-11 computer controls the transmission from the AP modem to the AP simulator and back to the modem again.

A block diagram of the AP Fast DFE modem used in the test program is presented in Figure 2-3. The data rate of the modem is 2900 bps. All experiments in the test program have been run without coding and without interleaving. However, since we have demonstrated excellent performance at 2900 bps and since potential for higher data rates exists, future plans are to test performance with coding as well. Error correction coding and interleaving would serve to scramble burst errors. The purpose of an interleaver is to provide time diversity protection against lightning bursts and in nonvoice applications against fades.

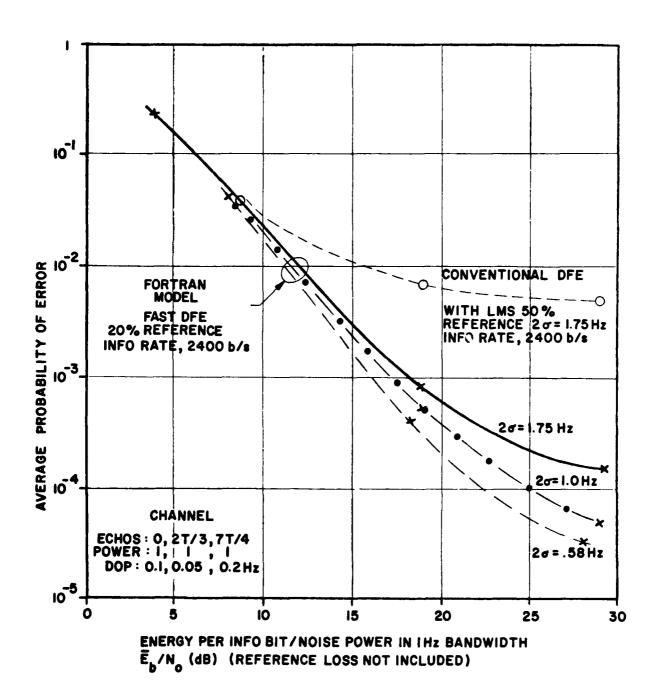


Figure 2-2 QPSK Performance Fading Channel Simulation Results

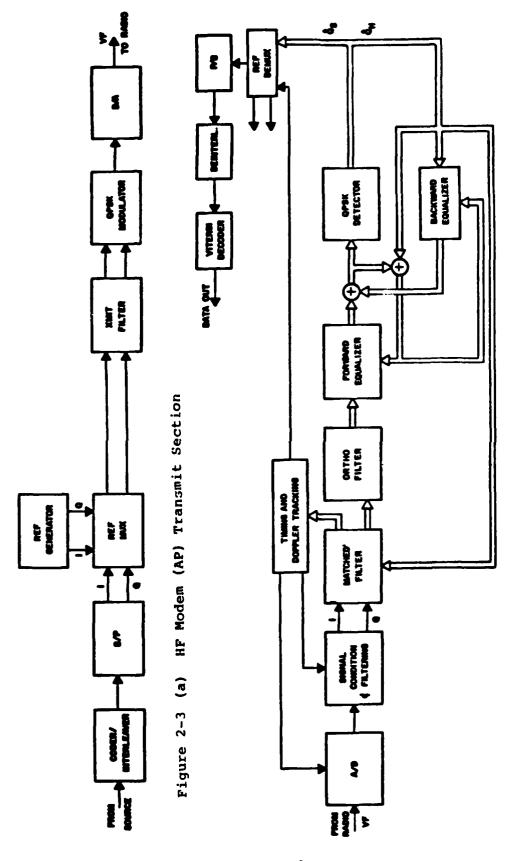


Figure 2-3 (b) HF Modem (AP) Receive Section

The receiver of the Fast DFE modem consists of an adaptive matched filter, a forward filter equalizer, a backward filter equalizer, and a QPSK detector followed by the reference DEMUX. Functions to be added are deinterleaver and decoder. The forward filter equalizer also contains an orthogonalizing filter which equalizes the tracking modes. The Reference DEMUX strips out the reference. When coding is inserted, the DeInterleaver/Decoder would use soft decisions to recreate the information stream. At the output, average bit error rate and output probability statistics are collected for evaluation.

In the experimental model, a reference signal of 1400 bps is time division multiplexed into the 2900 bps data stream to provide a channel rate of 4300 bps. At the output of the transmitter a spectral control filter is used to meet the 2.7 KHz voice channel bandwidth constraint. The interface with the radio requires a digital to Voice Frequency (VF) converter. This shifts the baseband spectrum to the center of the allocated radio channel. This analog interface was not required for the channel simulator tests in this program.

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3.0 MODEM TEST CONFIGURATION

The test configuration used two AP-120B array processors, each controlled by a PDP-11/70. One AP realizes the DFE modem, and the other realizes the channel simulator, the SIGNATRON S250 HF Channel Simulator, [3.1] developed for RADC. Specifications for the HF Media Simulator are given in Table 3-1.

3.1 <u>Test System Description</u>

Signals between the modem and the simulator were transmitted digitally under the control of the PDP-11/70. A shared resident common area in the PDP-11/70 was used as a data buffer between the two tasks. Figure 3-1 shows a block diagram of this configuration.

Because the modem transmitter has the complex signal available, the signal was transmitted to the simulator, avoiding the need for the Hilbert transform in the simulator. A sampling rate of 8.6 kHz at the input and output of the simulator was used. The only other change to the simulator was to make it accept, operate on and output a frame of digital samples (approximately once every 20 milliseconds). The original S250 simulator received and put out samples through an analog interface, and operated on a sample-by-sample basis.

Two tasks in the PDP-11/70 control the transfer of data between the modem and the simulator. Each task communicates with the associated AP-120B by means of the LITES and SWR registers in the host-AP interface. The two tasks communicate with each other via two status words in the shared common area. During operation, the modem program requests a buffer by setting a bit in the LITES register. The host task notices this bit and checks a status word to see if the buffer is empty. When it becomes empty, the host task sets a bit in the SWR register. The AP,

Table 3-1 HF Media Simulator Specifications

Channel Parameters

Number of Channels 1

Input Impedance 600 ohm, balanced

Bandwidth 300 Hz to 4000 Hz

Relative Delay Flat within 50 microseconds

Input Signal Level +10 dBm maximum

0 dBm nominal -10 dBm minimum

Median Output Signal Level

0 to -30 dBm, adjustable

Additive Gaussian

Noise Level

-10 to -40 dBm or off, adjustable

Impulse Noise Maximum output of the A to D

converter to lesser values in convenient, adjustable steps 0 to 1 fade per second in

.1 second steps.

Noise Bandwidth 4KHz

Path Parameters

Number of Paths

Available

1 to3 selectable

Doppler Frequency

per Path

0, .1, .5, 1, 2, 5, 10, 20,

50 Hz either positive or

negative

Delay per Path

0 to 10 milliseconds, adjustable

Signal Level per

Path

0 dBm to -30 dBm or off, adjustable

Path Noise -3 dBm to -40 dBm or off, adjustable

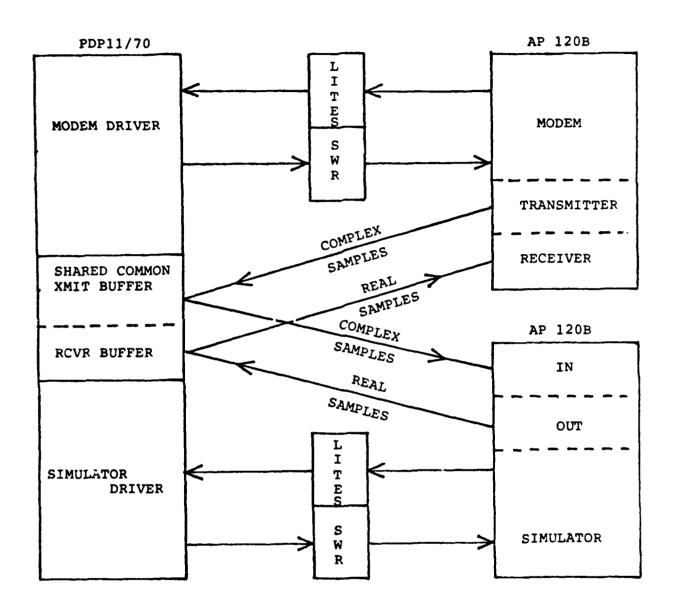


Figure 3-1 Test Configuration

notices this bit, clears the request bit in the LITES register, and executes the transmitter code. It then waits until the host task has cleared the buffer available bit in the SWR register, which the task does when it notices that the request has been turned off, and then the modem requests another transmitter buffer. The host task again notices this request, and if the host transmit buffer is empty, transfers data from the AP to the shared common area and then marks the buffer full in the associated status word. The simulator host task similarly responds to requests from the simulator AP code by transferring the data from the common area to the input buffer of the AP and marking the buffer empty. A similar procedure is followed for simulator output/receiver input.

3.2 Modem Information Rate

The basic information rate of the system during all tests was 2900 information bits/second plus a time division multiplexed reference of 1400 bits/second, or 4300 bps composite data stream. There were no interleaver/codec tests performed in this test effort.

3.3 Test Validation

The test system was validated in several ways. First, to establish spectral occupancy, the simulator was replaced by a program which performs an FFT on the modem transmitter output signal and prints out the spectrum. This program used the same software interface to the modem task as the simulator. A second validation test, consisting of specifying an additive White Gaussian noise channel and measuring the resulting probability of error for a range of specified signal-to-noise was performed. The probability of error was compared to theoretical probability of error and the signal-to-noise ratios were calibrated.

SECTION 3 REFERENCES

[3.1] L. Ehrman, "Tropo Diversity Simulator Development", Final Report No. RADC-TR-74-188, July 1974.

4.0 PERFORMANCE TEST RESULTS

The SIGNATRON Fast DFE modem in an array processor configuration was tested over an HF channel simulator realized in a second array processor. The array processors in this experimental configuration were AP-120B systems. The purpose of the tests was to evaluate the tracking and equalization ability of the Fast DFE modem algorithm under HF fading multipath channel conditions subject to a 99% power bandwidth of 2700 Hz. Tests to include synchronization, time tracking, and carrier frequency acquisition and tracking were not included in this tandem array processor experimental test.

4.1 Modem Design Features

The initial modem design provided for a 2400 bps information rate, a 16% reference rate of 700 bps and a 2/3 rate error correction code of 1200 bps for a composite channel rate of 4300 bps. Quadrature Phase Shift Keying (QPSK) modulation at a 2150 Hz symbol rate was selected to realize the 4300 bps channel A transmit filter providing a 99% power bandwidth of 2700 Hz and exceeding the requirements of MIL-STD-100 was selected. The spectral occupancy of the SIGNATRON modem is shown Preliminary tests of the modem with this data in Figure 4-1. rate configuration showed poor tracking capability under fast Results using the 16% reference were confading conditions. siderably poorer than the initial Fortran modem version which This result was attributed to the refused a 20% reference. erence rate difference and the additional transmit filtering used in the array processor modem. The modem was reconfigured keeping the same channel rate of 4300 bps but with an increase in the reference rate to 1400 bps. The initial measurement effort and modem reconfiguration precluded the intended implementation of error correction coding/interleaving into the modem. Thus the

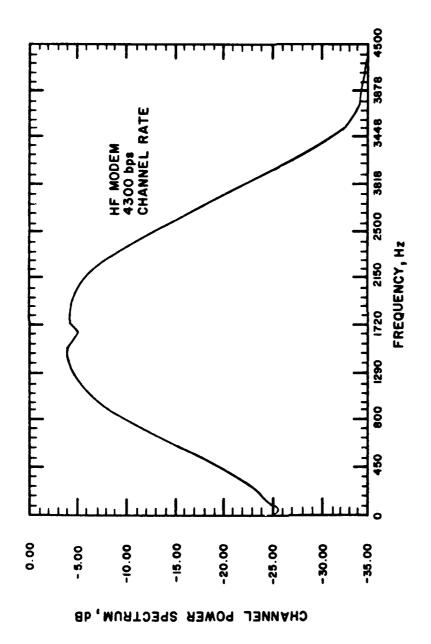


Figure 4-1 Spectral Occupancy of Transmitted Waveform SIGNATRON AP-120B Test Modem

entire experimental test program was conducted at a 2900 bps information rate without error correction coding and with a 32% reference of 1400 bps. Subsequent fading tests showed that the performance difference between a 32% and 100% reference is about a factor of two in irreducible error rate under very fast fading channel conditions. Transmission of a 32% reference represents a 1.7 dB power loss in received information bit energy. This loss is included in the performance curves presented here.

Subsequent designs at the information rate objective of 2400 bps might use a different ratio of reference and data bits as well as error correction coding all within a channel rate of 4800 bps. Our tests of the modem at a 4300 bps channel rate provide good correlation with the performance of a subsequently designed error correction coding modem because of the low sensitivity to small channel data rate changes.

4.2 Modem Test Parameters

The SIGNATRON Fast DFE modem concept utilizes an adaptive configuration mode which, in effect, tailors the number of equalizer taps and the equalizer loop bandwidths to the average fading conditions. Initial tests were performed using different sets of fixed configurations in order to establish a performance Resolution of problem areas in particular the refbaseline. erence rate increase and modem reconfiguration resulted in insufficient time for integration of the adaptive configuration modem. Some performance degradation relative to the data presented here may result in an adaptive configuration system. Since the average fading conditions change slowly, our judgement is that this performance degradation will be small. The fixed configuration for the Fast DFE used in each test is identified by the number of taps and loop bandwidth in Hz for each equalizer sub-These subsystems are the matched filter (MF), forward filter (FF), and backward filter (BF). As an example the maximum configuration for largest delay spread is described by

DFE: MF, FF, BF TAPS: 21, 15, 14 BW: 4, 2.5, 1.5

(Hz)

The tap spacing of the matched filter is 0.232 msec which is one-half a QPSK symbol interval. The tap spacing of the forward filter and the backward filter is equal to the QPSK symbol interval. The matched filter spans 4.9 msec of delay and the forward filter spans about 7 msec of delay.

4.3 Test Program

The test program consisted of eight major tests which are summarized in Table 4-1. The channel parameters which were varied over the fade rate expressed as a 2s Doppler spread, the number of paths, the Doppler shift on each path, and the path delays. Tests were performed at Doppler spreads up to 2 Hz and path delays of up to 5 milliseconds. The signal and noise levels were adjusted to achieve a range of E_h/N_h values. With a direct interface between the array processors, it was necessary to recalibrate the signal-to-noise ratio for these tests. The results of this calibration give a signal-to-noise ratio of 0 dB in a 4300 Hz bandwidth when the signal is set 2 dB higher than the The average energy per information bit divided by the noise spectral density in watt/Hz for our 2900 bps modem is 1.7 dB larger than the calibrated signal-to-noise ratio. the error correction coding/interleaving was not implemented in the modem, no tests were performed with impulsive noise.

Tests 1, 2, and 3 are non fading conditions with Doppler shift parameters. Tests 4 through 7 are frequency selective fading tests. Test 8 is a flat fading test. Test 4 was added to the program because it is the test channel used by Watterson [4.1] for evaluation of parallel tone modems and by the Harris Corporation [4.2] for evaluation of their serial tone modem. The results presented here in this section for the SIGNATRON modem are compared with these other modem results in the next section.

4.4 Test Results

Figures 4-2 through 4-8 present the results from the modem tests of Table 4-1. A summary for each test curve follows.

TEST 1 & 2: Non Fading and Doppler Test, Figure 4-2

This test illustrates the performance of the SIGNATRON modem on a non fading white Gaussian noise channel. In the minimum configuration; DFE(A), the degradation relative to ideal is about 3.5 dB at 10^{-3} bit error rate even with Doppler shifts up to 5 Hz. This 3.5 dB is primarily due to a 1.7 dB reference loss, adaptation self noise, and an intersymbol interference (ISI) penalty due to transmitter bandlimiting. In the maximum configuration; DFE(B), the degradation is larger because of additional adaptation self noise with the increase in number of taps.

TEST 3: Doppler Echo Test, Figure 4-3

This test illustrates the ability of the modem to track an infinitely deep frequency selective fade. By placing a Doppler shifted echo at 0.5 msec with a 0.5 Hz Doppler, this fade repeats every two seconds. The worse case error rate is extrapolated from the worse case mean square error at the QPSK detector input. This test is an example of a serial modem

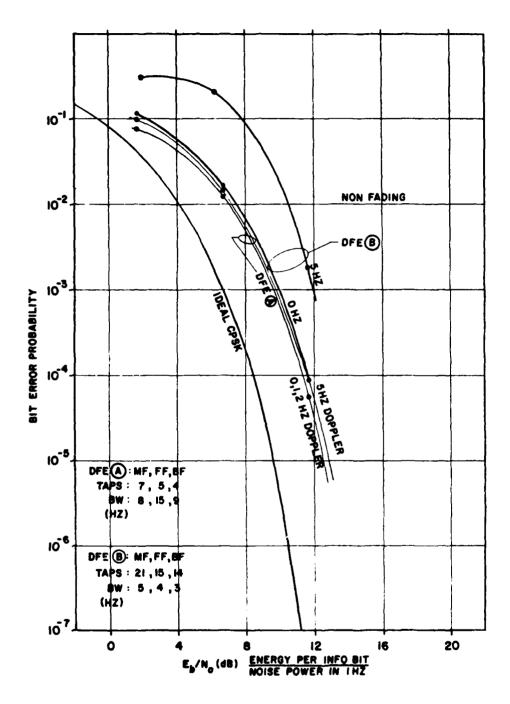


Figure 4-2 Non Fading and Doppler Tests (Test #1, 2)

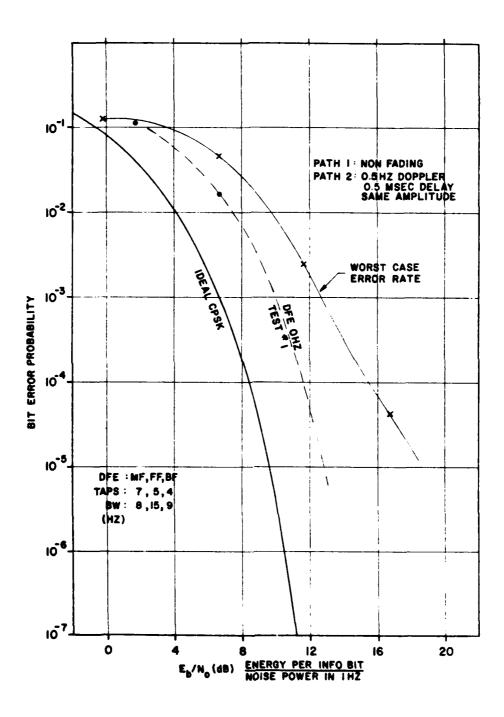


Figure 4-3 Doppler Echo Test, #3

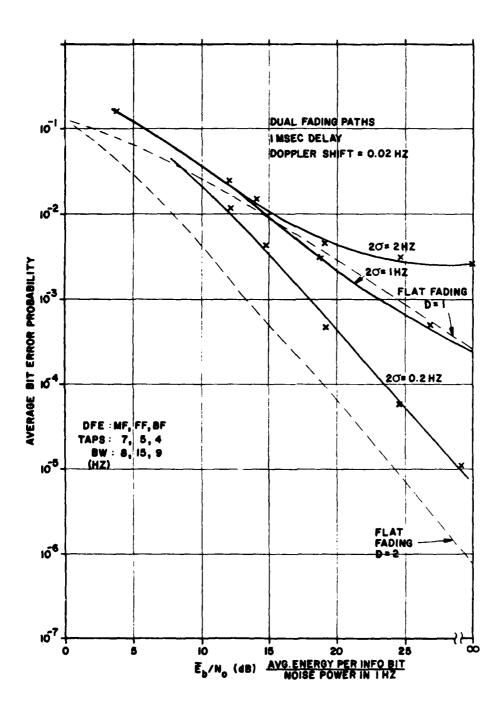


Figure 4-4 Dual Fading 1 MS Test, #4

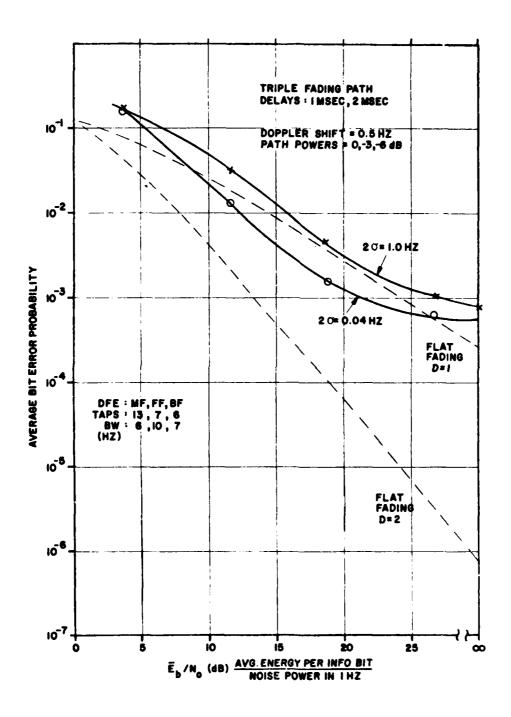


Figure 4-5 Triple Fading 2 MS Test, #5

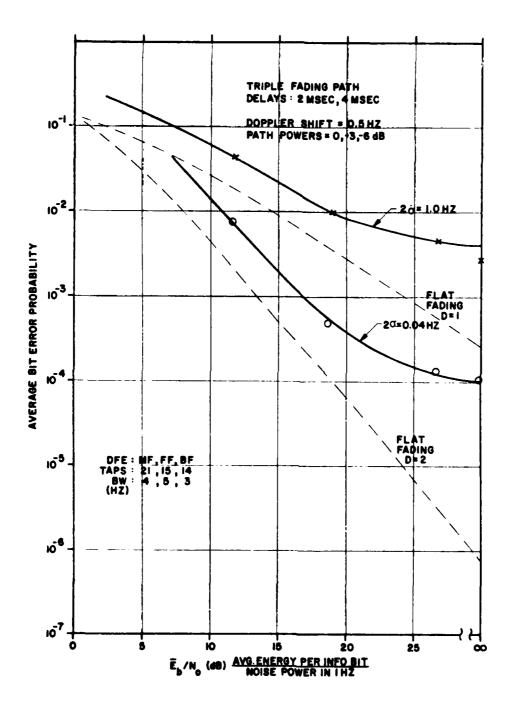


Figure 4-6 Triple Fading 4 MS Test, #6

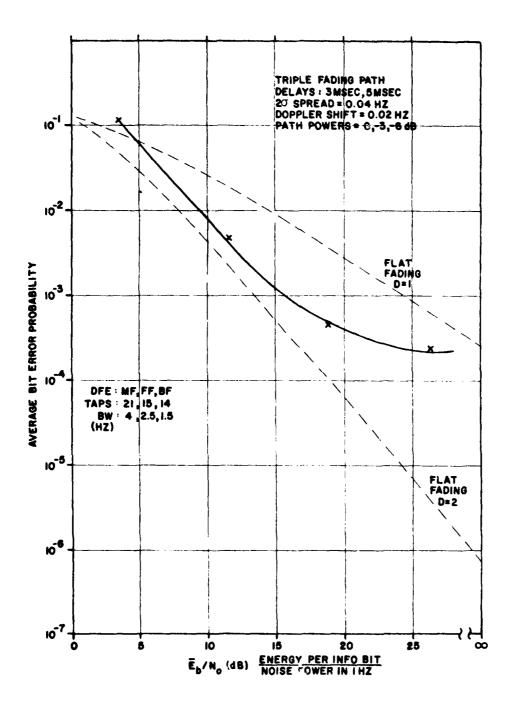


Figure 4-7 Triple Fading 5MS Test, #7

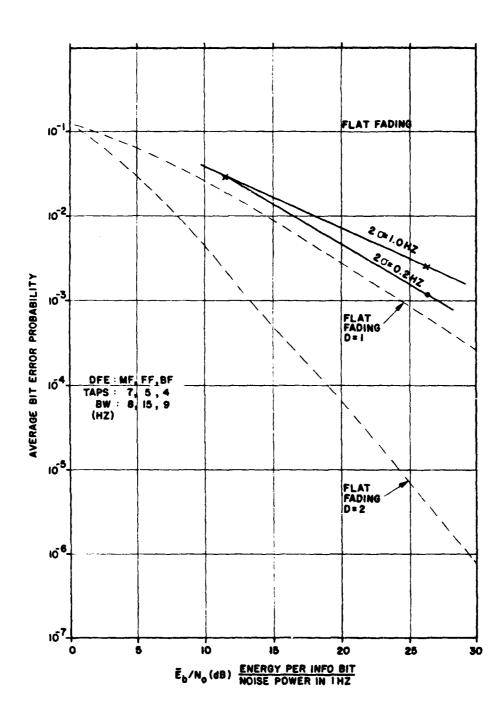


Figure 4-8 Flat Fading Test, #8

operating in a fade condition for which parallel tone modems without coding or a linear equalizer serial tone modem would have an irreducible error rate. The no multipath curve from test #1 is shown as a dashed line in Figure 4-3 to show the small ISI penalty under this deep selective fade condition.

TEST 4: Dual Fading 1 MS Test, Figure 4-4

This test is a replica of the test used by Watterson [4.1] and Harris Corporation [4.2] for previous modem evaluations. It consists of two fading paths separated by 1 msec delay each with the same 2σ Doppler spread. The performance results are plotted with respect to ideal flat fading conditions for no and dual diversity. The best that can be done with this channel is bounded by the dual diversity curve. This best performance is achieved when all the energy in both fading components is used with no ISI or tracking penalty. At the lower Doppler spread of 0.2 Hz there is no tracking penalty and performance is within 4.5 dB of ideal dual diversity. The results show a very significant implicit diversity gain when the fading is slow. Doppler spreads on HF channels are on the order of tenths of Hz although much of the testing is done at around 1 Hz as this represents a worse case condition for mid latitude paths.

At 1 and 2 Hz most or all of the implicit diversity advantage is sacrificed to a tracking degradation. However, the Fast DFE performance is quite acceptable at a 1 Hz Doppler spread where approximate ideal flat fading conditions are achieved. By contrast, a parallel tone modem under the same circumstances without error correction coding would do no better than the flat fading no diversity bound.

TEST 5: Triple Fading 2 MS, Test, Figure 4-5

The results here show loss in implicit diversity due to an ISI penalty for the slow fading 0.04 Hz Doppler spread. This ISI penalty is due to the design realization of the matched filter which results in non ideal matched filter weights. A matched filter design which would reduce this ISI penalty has been developed but not implemented. Note however that significant implicit diversity is still realized in the medium signal-to-noise ratio range. Furthermore even at a 1 Hz fade rate, performance is quite acceptable.

TEST 6: Triple Fading Test 4 MS, Figure 4-6

An ISI penalty limits the implicit diversity at low fade rates and large signal-to-noise ratio. The implicit diversity realized is still significant, however. Although tracking and an ISI penalty degrades performance significantly at a 1 Hz fade rate under these multipath delay conditions, successful operation is still achieved.

TEST 7: Triple Fading 5 MS Test, Figure 4-7

This test shows that even as much as 5 msec of delay can be equalized by the modem if the fading rate is not too large. Note the implicit diversity gain at medium signal-to-noise ratio values.

TEST 8: Flat Fading Test, Figure 4-8

These curves show the performance under flat fading conditions at 2σ Doppler spreads of 0.2 and 1.0 Hz. The degradation from ideal flat fading is about 2.5 dB at the lower fade rate. This degradation correlates with the measured degradation at low signal-to-noise ratio values (where the errors are made on a fading channel) in the non fading performance curve of Figure 4-2. Some tracking degradation is shown at the 1.0 Hz Doppler spread.

SECTION 4 REFERENCES

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5.0 MODEM PERFORMANCE COMPARISONS

A series of tests on parallel tone modems by Watterson [5.1], and on two serial tone modems developed by Harris [5.2], and GTE Sylvania [5.3] provide a basis for modem performance comparison. Because of different test conditions, data rates and modem realizations, performance comparison requires more than a casual examination of bit error rate curves.

Although the results for the SIGNATRON FAST DFE modem are very promising for an HF application, the following two factors must be considered in a comparative evaluation with other modem techniques.

- The SIGNATRON modem tests were not performed through a radio and did not include analog interfaces including real transmitter and receiver filters.
- Synchronization and carrier acquisition/tracking subsystems were not implemented for the tests reported here.

The extent of the degradation associated with these two factors is not known but it is our estimate that they are small.

5.1 <u>Test Cases for Comparison</u>

There is considerable performance data available for the flat fading (single path) and the dual fading path suggested by Watterson [5.1]. This latter channel has two "skywave" returns which are spaced by 1 millisecond and they fade with a 2 σ Doppler spread of 1.0 Hz. In general the more echoes, the easier it is for the equalizer to track because it is less likely that all echoes will simultaneously become small. The Watterson two path model has thus become a good standardized test case. Watterson tested conventional parallel tone modems on this channel and the

results are given in his report [5.1]. This channel was also used in the Harris modem evaluation [5.2] for comparison with parallel tone modem techniques.

We compare the SIGNATRON 2900 bps modem with other modem techniques at 2400 bps because this is the closest rate. This 20% rate difference favors the other modem techniques since the modems are performing at the edge of bandwidth capability. All of the modems are uncoded except for the parallel tone MX-190 modem which used a rate 16/25 block code. Although the simulators used on some of the tests were not exactly the same, no appreciable performance difference is anticipated from this factor. The Harris modem test data cited here is from tests on the same software simulator.

The fairest comparison is on a peak power basis because HF radios are peak power limited. A comparison [5.2] of the Harris modem with parallel tone modems used peak bit energy $\rm E_{\rm pb}$ rather than average bit energy $\rm E_{\rm b}$. We follow the same convention in the comparison presented here. The peak-to-average ratios assumed for the modem comparison were

SIGNATRON (SIG) Modem: Harris (HRS) Modem:	$\begin{pmatrix} 1 & dB \\ 1 & dB \end{pmatrix}$	SERIAL TONE
USC-10: ACQ-6: MX-190:	7 dB 7 dB 7 dB	PARALLEL TONE

Thus against E_{pb}/N_0 , the SIGNATRON modem results are shifted 1 dB to the right of the curves presented in Section 4.

5.2 Modem Comparisons

The flat fading channel results are shown in Figure In the flat fading tests, the two serial modems compared perform almost the same and both gain a large number of dB over the parallel tone modems. Most of this improvement is due to the peak-to-average ratio. In the frequency selective fading tests which are shown in Figure 5-2, the Harris and SIGNATRON modem realize almost exactly the same implicit diversity when the fading is slow. The performance advantage of these modems over the parallel tone modems is very large under these conditions. Under faster fading conditions, the Harris modem has a better irreducible error probability but the SIGNATRON modem does a little better under weak signal-to-noise ratio conditions. of the SIGNATRON and Harris modems under extremes of multipath and Doppler spread generally showed superior performance at high signal-to-noise ratio for the Harris modem where the data rate differential would be expected to have the greatest impact. These extreme multipath/Doppler spread conditions are an area where further performance improvement of the SIGNATRON modem is possible and planned.

In comparison with parallel tone modems under the faster fading conditions, both the SIGNATRON and Harris modem still have a significant performance gain even over the coded MX-190 system. Both the Harris and SIGNATRON modems have not included error correction coding.

A direct comparison with the GTE modem performance results [5.3] is not possible because most of the GTE modem tests used an ARQ strategy with a feedback link.

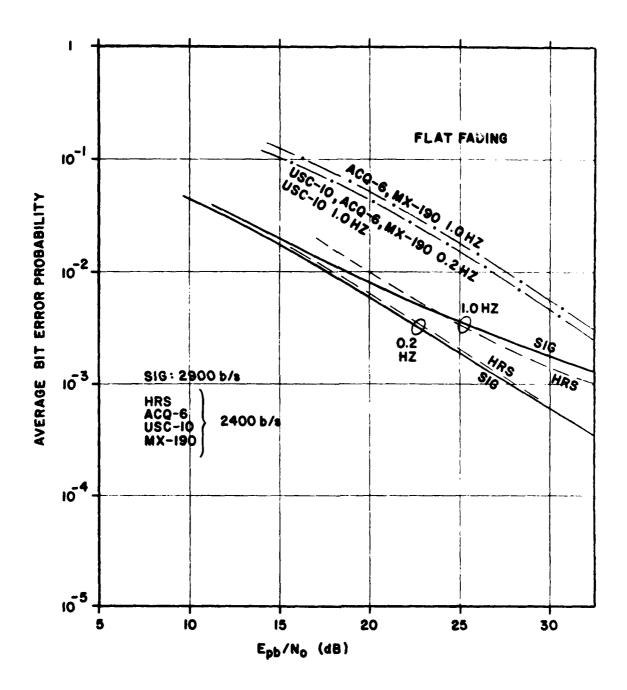


Figure 5-1 Flat Fading

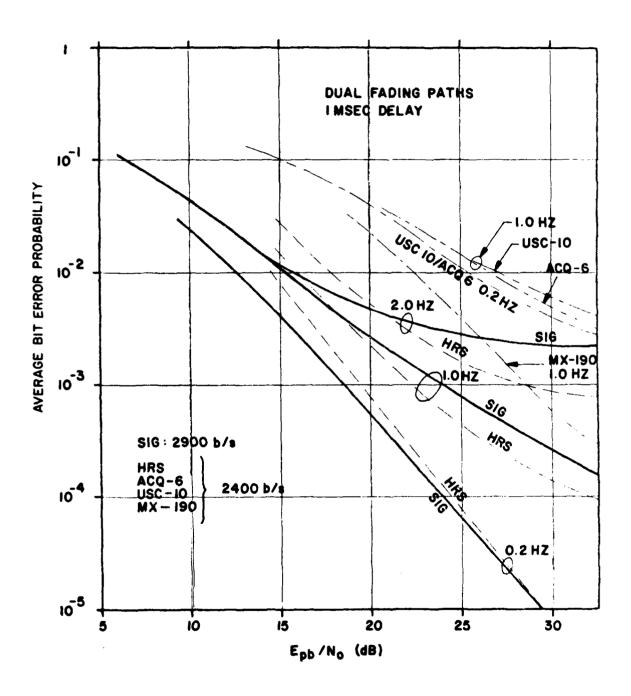


Figure 5-2 Watterson Test Channel

A comparison of the SIGNATRON AP modem with a software simulation model of a .man filter equalizer has been performed on the Watterson channel at a 1 Hz Doppler spread. earlier program [5.4], SIGNATRON developed a general software simulation of an HF equalizer for NOSC, San Diego, California. At NOSC, Dr. L.E. Hoff modified and tested a Kalman filter equalizer on the Watterson Channel. The performance comparison is shown in Figure 5-3. Note that the performance of the 2900 bps FAST DFE is comparable to the 2400 bps Kalman simula-Indeed, the higher data rate Fast DFE outperforms the Kalman filter at low signal-to-noise ratios because only a 32% reference (1.7 dB loss) was used in the former whereas the latter used a 50% reference (3 dB loss). This feature of achieving nearly optimum performance with a reduced complexity approach has been the fundamental goal of our HF modem development program.

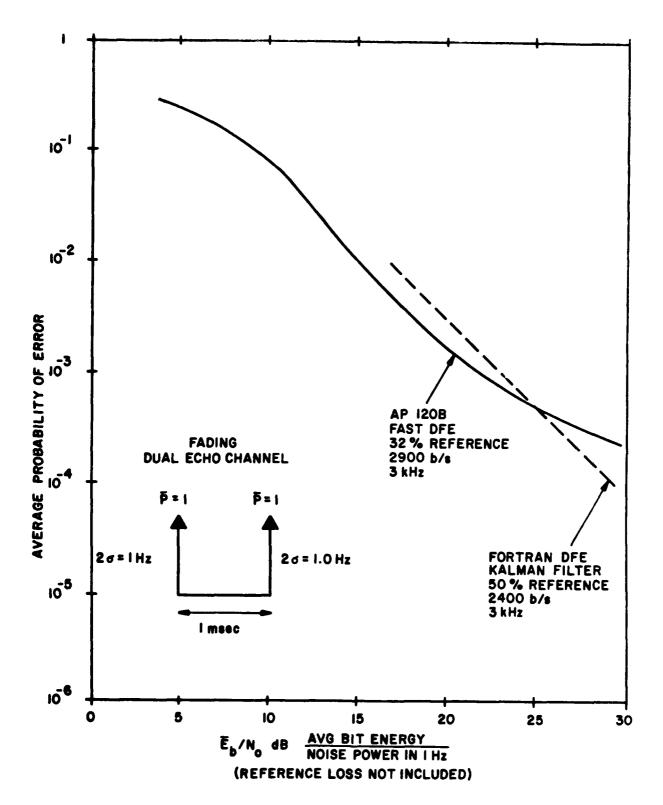


Figure 5-3 Comparison of SIGNATRON AP-120B Modem Tests to Kalman Filter Equalizer

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6.0 CONCLUSIONS AND RECOMMENDATIONS

A new serial tone HF modem developed by SIGNATRON has been tested on a HF channel simulator. The Fast DFE modem operates at 2900 bps information rate with 1400 bps of reference overhead for equalizer adaptation. The resulting 4300 bps channel rate is QPSK modulated into a 2700 Hz 99% power bandwidth as in a typical HF radio channel application. The Fast DFE modem uses an orthogonal vector adaptation technique which has greatly improved tracking capability relative to the conventional Least Mean Squares gradient technique such as that used in troposcatter equalizer applications. Modem complexity is minimized by using vector updates as opposed to matrix updates required in a Kalman filter equalizer. A comparison with a software Kalman Filter approach shows that virtually all the performance is realized with a considerably simpler modem configuration.

The modem and HF simulator are both realized in separate FPS-120B array processors. An array processor realization selected for flexibility of parameter and design modifications during this experimental phase. The modem is not completely real time and does not have an analog interface to an external source and/or radio system. The modem and HF channel simulator interface through QPSK baseband digital samples. The HF channel simulator was developed by SIGNATRON prior to this program. It can generate up to 6 fading paths with typical HF path delay and Doppler characteristics.

A series of non fading, frequency selective rading, and flat fading tests of the SIGNATRON modem were performed. The results of these tests were compared with previous parallel tone and serial tone HF modem tests. The major findings can be summarized as follows:

- The SIGNATRON modem operates successfully with Doppler spreads up to 1 Hz and with delay spreads up to 5 milliseconds. For these more difficult conditions performance is close to ideal flat fading. For less difficult conditions, a significant implicit diversity improvement over flat fading is realized.
- In all test cases, the SIGNATRON modem significantly outperforms conventional parallel tone modems such as the USC-10, ACQ-6, and MX-190. In many cases the dB gain of the serial tone modem is 10 dB or more.
- In a comparison with the Harris serial tone modem, the test results show comparable performance, i.e., there are sets of conditions where one or the other modem has better performance. Under large Doppler and multipath spread conditions, the SIGNATRON modem had a larger irreducible error rate.

These results and the low complexity of the Fast DFE approach lead to a recommendation for the development of a hardware version of this HF modem. The recommended steps in this development are as follows:

- (1) in the array processor configuration modify the matched filter design so as to further improve performance under large multipath and Doppler conditions
- (2) integrate error correction coding and interleaving into the array processor configuration. These subsystems will provide additional fade margin, protection against burst noise, and for non speech applications, time diversity protection against fading
- (3) development of a real time capability and analog interface in the array processor for a field test evaluation

- (4) modification of data rates to the standard 2400 bps for better comparison with other modems.
- (5) hardware development using micro programmable chip technology
- (6) simulator and field tests of the hardware modem.

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